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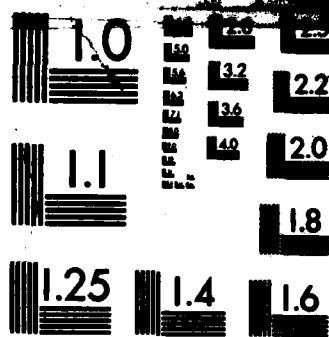
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# Progress in Geotechnical Dynamic Centrifuge Modeling

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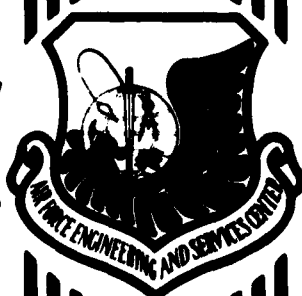
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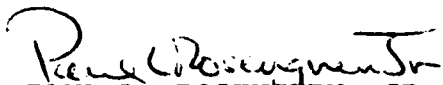
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This report covers work performed between May 1984 and August 1984. The AFESC/RDCS project officer was Captain Paul L. Rosengren, Jr.


This report discusses the history and technical advances of centrifugal modeling of highly dynamic geotechnical events. Difficulties and validity of centrifuge modeling technology are presented along with examples of dynamic centrifuge modeling and advantages of using centrifuge modeling technology to study the behavior of geotechnical structures.

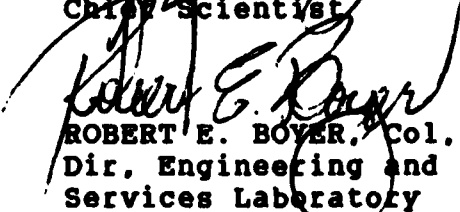
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This technical report has been reviewed and approved for publication.

  
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## SECTION I

### INTRODUCTION

#### OBJECTIVES

A great upsurge in the usage of the centrifuge modeling technique for geotechnical studies has taken place in recent years. This technique has a unique potential to provide a means of conducting small-scale model studies at prototype stress levels. Although some difficulties are encountered at present, the centrifuge technique appears to show promise in dynamic studies of geotechnical structures, and other geotechnical-related phenomena. The potential of centrifuge technique for use in geotechnical modeling was first recognized (independently) by Davidenkov (Reference 1) and Pokrovsky in 1932 (Reference 2), and also (independently) by Bucky in 1933 (Reference 3). Pokrovsky published monographs in 1935 (Reference 4) which gave real recognition to the technique. Bucky did not pursue the technique to any significant degree. Today several centrifuges, worldwide, that are used for geotechnical modeling purposes (Figure 1). The objectives of this paper are to summarize the principles of dynamic centrifuge modeling and to provide an overview of its development in recent years.

#### AREAS OF APPLICATION

Broadly, the centrifuge modeling technique may be used in the following four areas: (1) phenomenological study of geotechnical structures whose behavior is poorly understood; (2) verification of analytical procedures; (3) parametric and sensitivity studies; and (4) direct modeling to validate a design or to assess the safety of an existing structure.

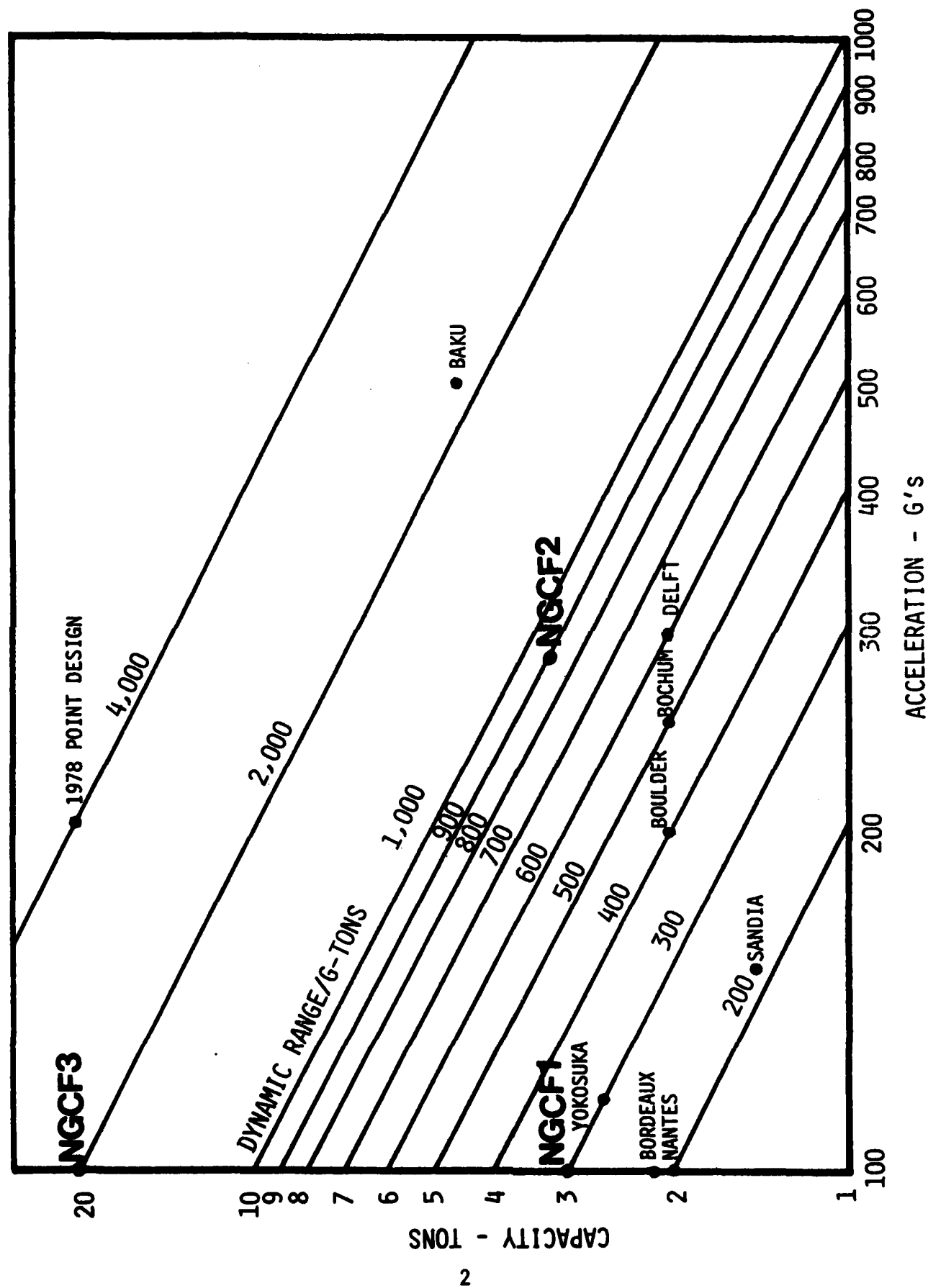


Figure 1. 2nd-and 3rd-Generation Swing Basket Geotechnical Centrifuges

## PRINCIPLES OF DYNAMIC CENTRIFUGE MODELING

The highly complex and nonlinear nature of the stress-strain behavior of soils requires that any model studies be carried out at prototype stress levels. The stress distribution in a soil mass depends on the self-weight of soil itself. The prototype stresses can be simulated in a small-scale model by carrying out the model experiment under increased gravity (Figure 2). The centrifuge technique provides a means of increasing the gravity by centrifugal acceleration.

If a certain prototype structure is to be modeled to a scale of  $N$  ( $N > 1$ , eg:  $N = 100$ ), the model experiment should be carried out at a centrifugal acceleration of  $Ng$  (eg:  $100g$ ). The stresses at geometrically similar points in prototype and model would then be identical, as shown in Figure 2. The scaling laws (Table 1) associated with other quantities of interest can be derived using dimensional analysis.

The simulation of dynamic events in the centrifuge requires that certain similitude conditions be satisfied. Considering the simulation of an acceleration history in a centrifuge:

(1) model frequency is  $N$  times larger than the prototype frequency; (2) model amplitude is  $N$  times larger; and (3) model duration is  $N$  times shorter. Moreover, the energy in the model is  $N^3$  times smaller than that in the prototype. Hence, in simulating an explosive loading in a centrifuge model, the weight of explosive required would be  $N^3$  times smaller than that used in the field, provided identical explosive types are used. For example, a field explosion with 8000 pounds of PETN can be simulated in the centrifuge with 3.65 grams of PETN at a centrifugal acceleration of  $100g$ .

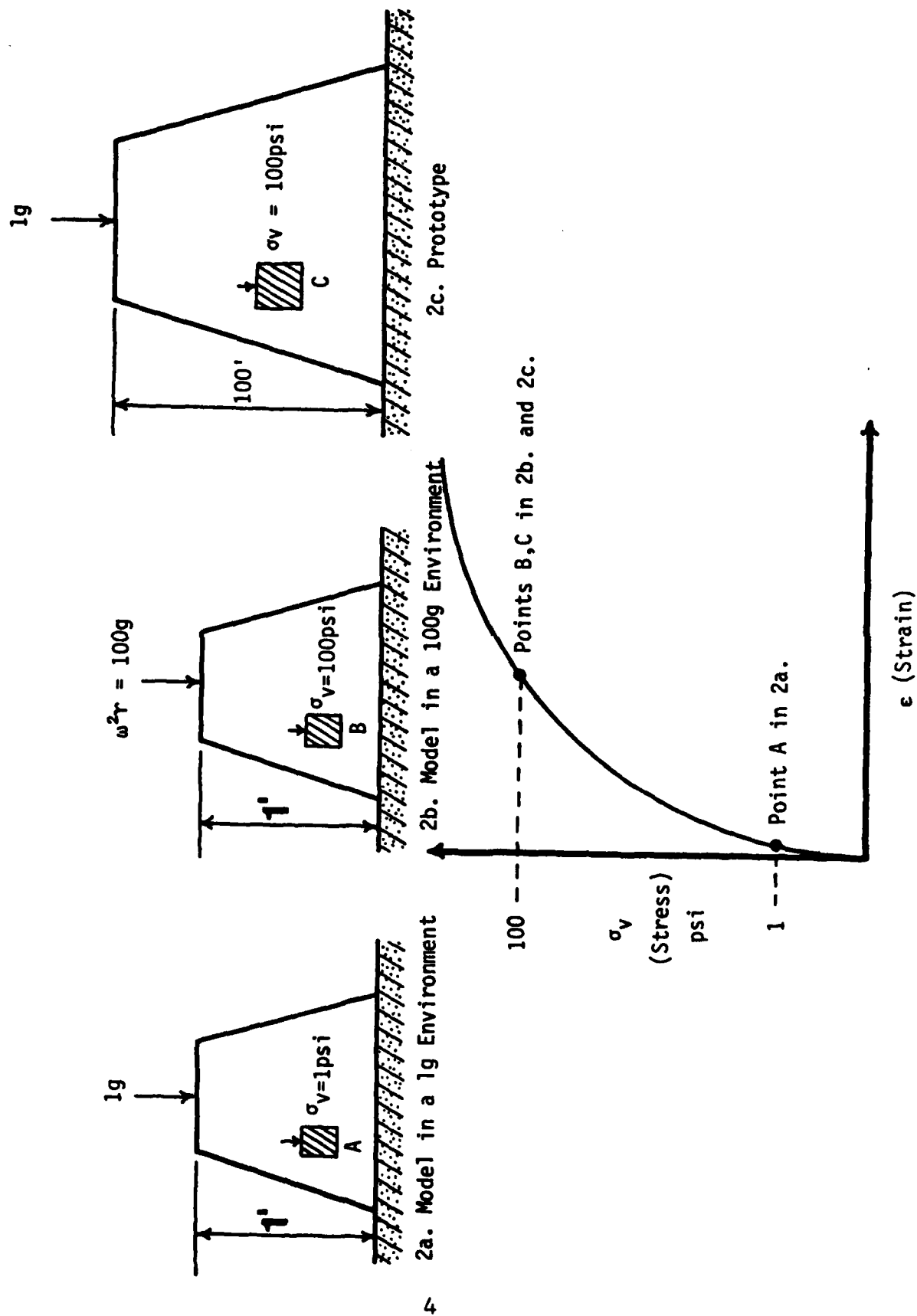


Figure 2. Centrifuge Modeling Concept

TABLE 1. SCALING RELATIONS

Quantity	Full Scale (Prototype)	Centrifugal Model at $n$ g's
Linear Dimension	1	$1/n$
Area	1	$1/n^2$
Volume	1	$1/n^3$
Time		
In Dynamic Terms	1	$1/n$
In Diffusion Cases	1	$1/n^2$
In Viscous Flow Cases	1	1
Velocity (Distance/Time)	1	1
Acceleration (Distance/Time <sup>2</sup> )	1	$n$
Mass	1	$1/n^3$
Force	1	$1/n^2$
Energy	1	$1/n^3$
Stress (Force/Area)	1	1
Strain (Displacement/Unit Length)	1	1
Density	1	1
Energy Density	1	1
Frequency		
In Dynamic Problems	1	$n$

## SECTION II

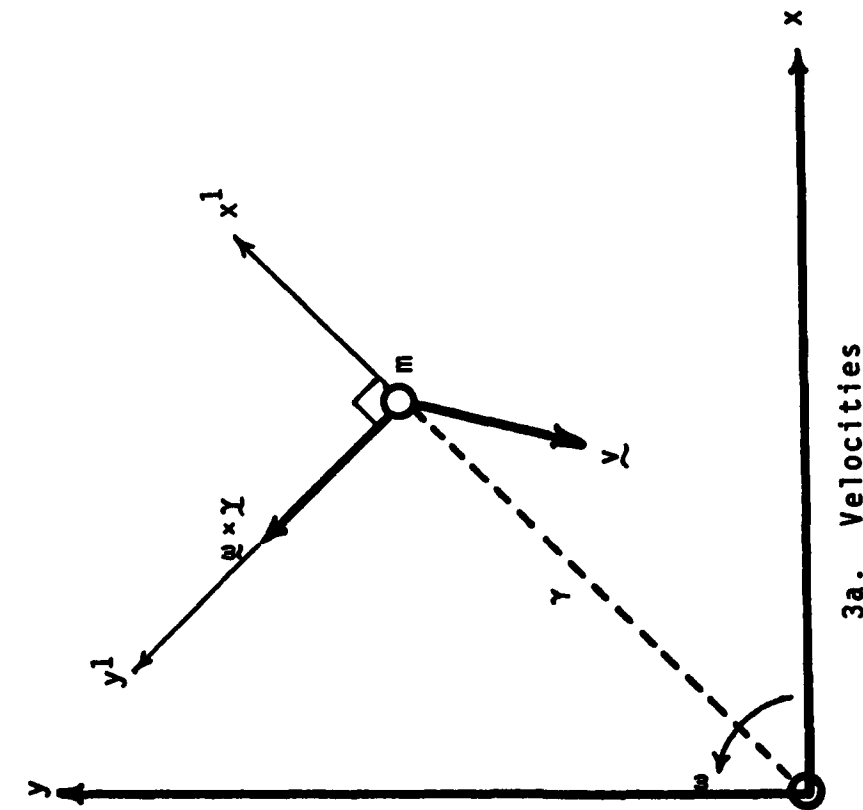
### DIFFICULTIES IN DYNAMIC CENTRIFUGE MODELING

Although considerable research has been devoted to geotechnical centrifuge modeling in the past, one still encounters some difficulties in carrying out a dynamic experimental test in a centrifuge. The simulation of earthquakes in the centrifuge challenges centrifuge experimenters. Some recent techniques used in small centrifuges for the simulation of earthquake events are: The piezoelectric shaker system (Reference 5), cocked-spring system (Reference 6), Scott's hydraulic simulator (Reference 7), Cambridge bumpy road actuator (Reference 8), Zelikson's explosive simulator (Reference 9), and Prevost's shaking plate (Reference 10). However, these techniques cannot be used to simulate a given variable frequency earthquake motion, although the piezoelectric shaker and Scott's hydraulic simulator appear promising. Recently, Anandarajah, et al, (Reference 31) have demonstrated the feasibility of simulating a variable frequency base motion using the piezoelectric shaker system. These techniques have not, however, been adapted to large centrifuges. The simulation of lateral pile vibration, foundation vibration, and explosive events is relatively simple and has been successfully done in the past (References 11 and 29).

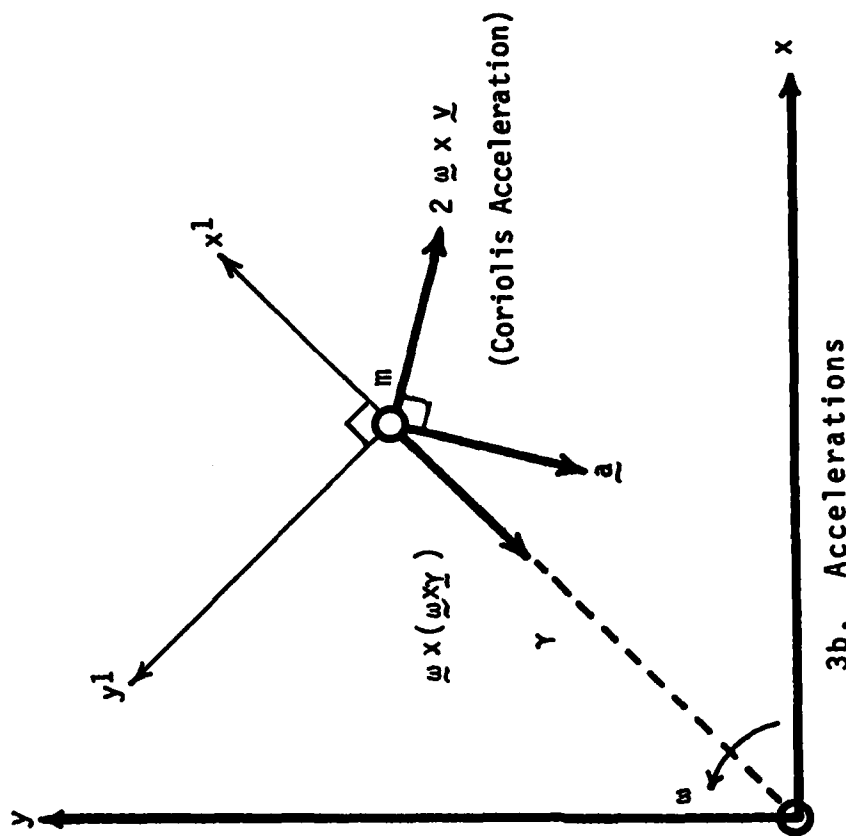
The presence of nearby rigid boundaries in a centrifuge model, and the consequent unwanted reflections of dynamic waves are major concerns in dynamic testing. Coe et al. (Reference 12) have demonstrated the presence of standing waves in a sand deposit confined in a centrifuge bucket and excited by surface dynamic inputs. It was further shown by Coe et al. (Reference 13) that certain reflection of low-amplitude dynamic waves can be attenuated by using appropriate absorptive material at bucket boundaries. A

stacked-ring apparatus was found to simulate simple shear conditions and used with good success in liquefaction studies. Anandarajah, et al, (Reference 14) have used a frictionless interface to inhibit undesirable reflections in the study of dynamic response of dams. A larger test platform would also help solve the boundary problem. Further research and development are required to properly handle the boundaries for different types of dynamic loads.

Figure 3 shows the velocity and acceleration fields of a rotating mass where the component  $2\omega \times v$  is the Coriolis acceleration. Thus, any dynamic excitation occurring in the plane of rotation or any movement occurring within the soil model would give rise to Coriolis acceleration. In 1975, Pokrovsky (Reference 15), by requiring that radial Coriolis acceleration be less than 10 percent of the centrifuge acceleration, gave an upper bound to the dynamic velocity as:  $V < 0.05\omega r$ . Also, by considering the motion of a particle under the influence of Coriolis acceleration, Pokrovsky suggested that the error can be neglected if  $V > 2\omega r$  for high-velocity events (eg: cratering event). Thus, an acceptable range of velocity according to Pokrovsky is  $2\omega r < V < 0.05\omega r$ . The Coriolis effect is unknown in the intermediate range of velocities. Anandarajah, et al, (Reference 16) has analytically shown that the earthquake-induced displacements of embankments in the centrifuge may be in error up to 18 percent. Further, theoretical and experimental studies are needed to evaluate the extent of Coriolis effects under different dynamic loading conditions.



3a. Velocities



3b. Accelerations

Figure 3. Velocity and Acceleration Components of a Rotating Mass,  $m$



A conflict in time-scaling can occur when dynamic events and pore pressure dissipation are likely to appear simultaneously in an experiment. The dynamic events occur as  $N$  times faster in a centrifuge model, whereas pore water diffusion occurs as  $N^2$  times faster. Modeling liquefaction is an example where such difficulty is encountered.

In such an event, it is necessary to slow down the pore water diffusion by a factor of  $N$ . This is fulfilled if the hydraulic permeability is decreased by a factor of  $N$ . The use of low-density or high-viscosity fluids decreases the permeability. It has been shown that the use of fluids such as oil and glycerine or mixture of these with water in some suitable proportion is an effective way of reducing permeability (Reference 17).

The use of prototype soil in the centrifuge model raises some questions since it results in improper modeling of particle size. One way of evaluating the influence of particle size on model data is to perform a series of modeling of model experiments, which will be discussed later.

Finally, the major difficulty of modeling in the centrifuge is the recreation of in situ soil conditions and the in situ loading history in the model. This, however, does not pose a major problem in such applications as verification of theories, parametric studies, understanding structural behavior, etc.

### SECTION III

#### VALIDITY OF CENTRIFUGE MODELING TECHNIQUE

As in any modeling technique, mathematical or physical, uncertainties are inherent in centrifuge modeling. It is, therefore, necessary to verify the validity of the test results in some manner. The technique of modeling of models is a means of verifying the validity of centrifuge scaling laws, boundary effects and particle size effects. This is based on the concept that the prototype predictions made by using the centrifuge modeling technique is independent of the scale used. For example, the prototype behavior of a 100-foot tall dam predicted by using a 1-foot tall centrifuge model of 100 g centrifugal acceleration should be reasonably close to the results predicted by using a 2-foot tall model at 50 g. A number of such modeling of model studies have been conducted for static loading cases (References 18 and 19) and the results confirmed the accuracy of centrifuge predictions under limited test conditions. Very few such studies can be found in the literature that deal with dynamic centrifuge modeling. Morris (Reference 20) performed a modeling series of towers resting on cohesionless soils and subjected to dynamic loading. The measured natural frequencies of the model tower at three different scales (80 g, 40 g and 26 g) obeyed the scaling law very well (Figures 4a and 4b).

An indirect way of gaining some level of confidence in the centrifuge results is by showing that the centrifuge predictions agree reasonably well with analytical predictions whose validity has already been established by some other means. A considerable amount of evidence is available in this respect, as shown in Figures 5 and 6 (Reference 21).

The final confirmation of the validity of centrifuge modeling technique can only be realized by showing that centrifuge predictions are reasonably close to field observations. Very few correlations of this nature are currently available for either static or dynamic loading conditions.

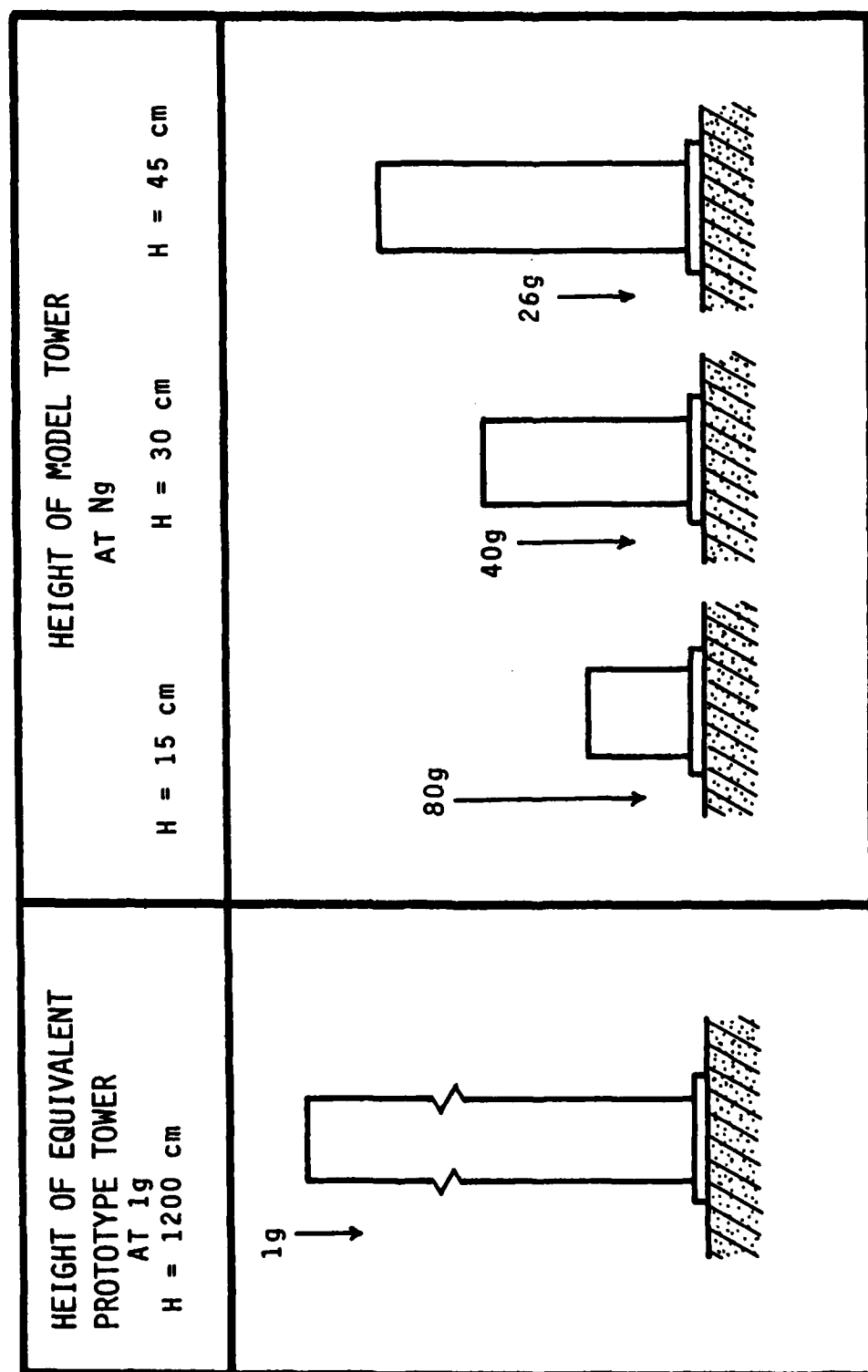
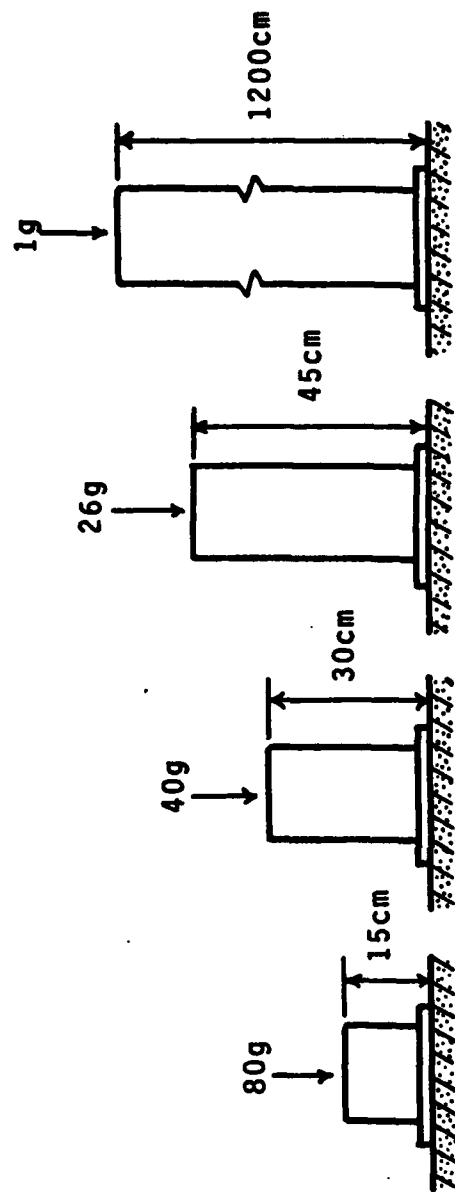


Figure 4a. Modeling of Models Example



$$H_p \times 1 = H_m \times N$$

or  $1200\text{cm} \times 1g = 15\text{cm} \times 80g = 30\text{cm} \times 40g = 45\text{cm} \times 26g$

( $H_p$  = Height of Model Prototype)  
 ( $H_m$  = Height of Model)  
 ( $N$  = Gravity Level)

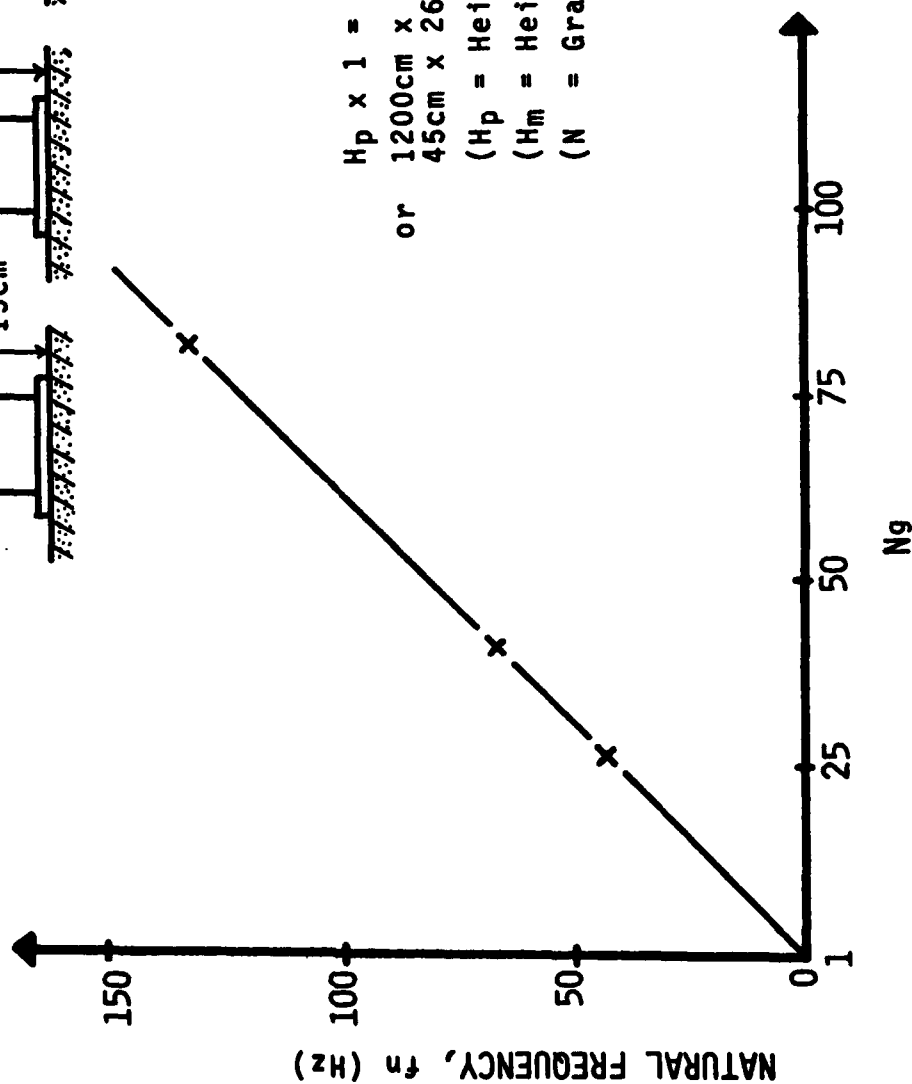
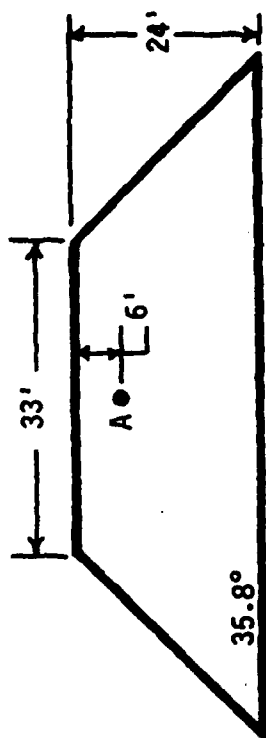


Figure 4b. Modeling of Models Example



MODEL 2 ( $\gamma_w = 125 \text{pcf}$ , w.c. = 14.5%)

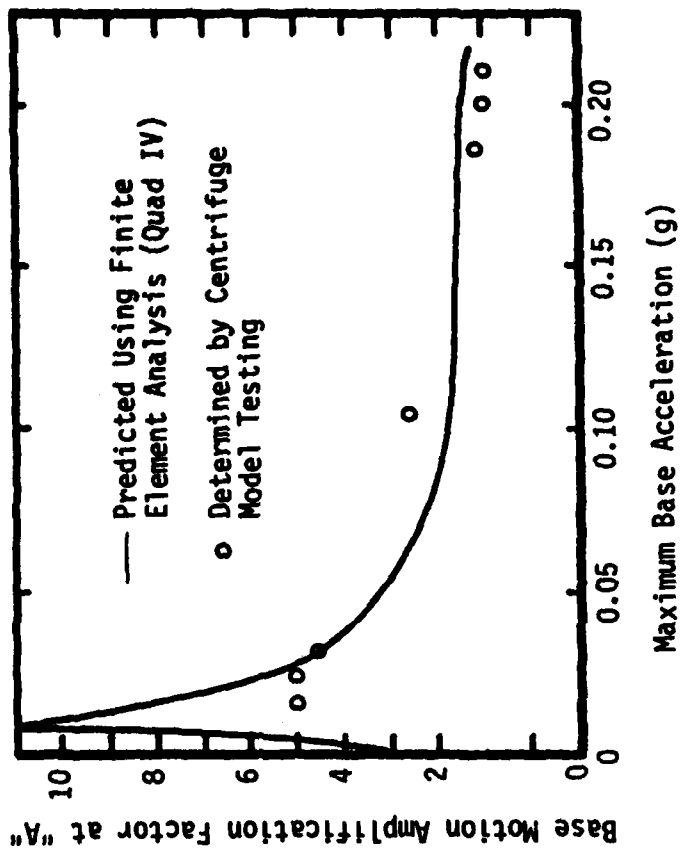
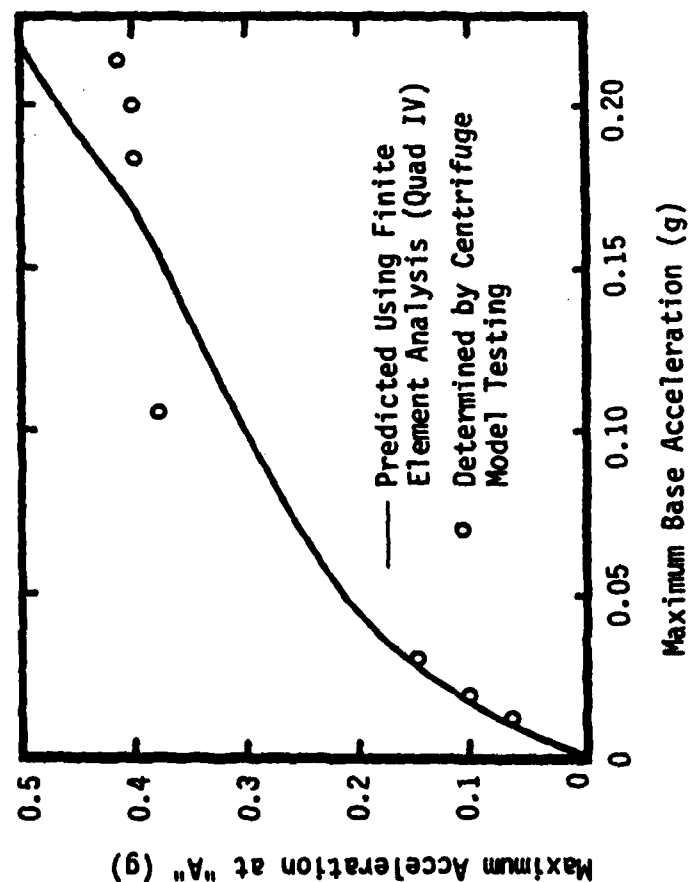
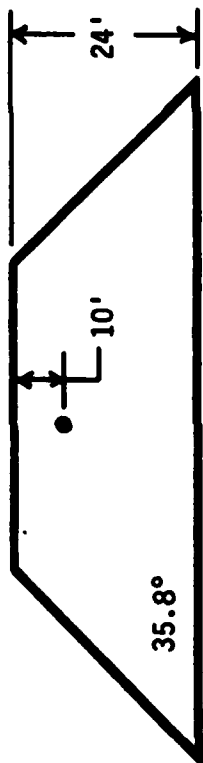


Figure 5. Comparison of Responses of Clay Embankment to Sinusoidal Base Motion Predicted by Finite Element Analysis and Centrifugal Model Testing-Model 2



Base Acceleration

MODEL 3 ( $\gamma_w = 115\text{pcf}$ , w.c. = 15.5%)

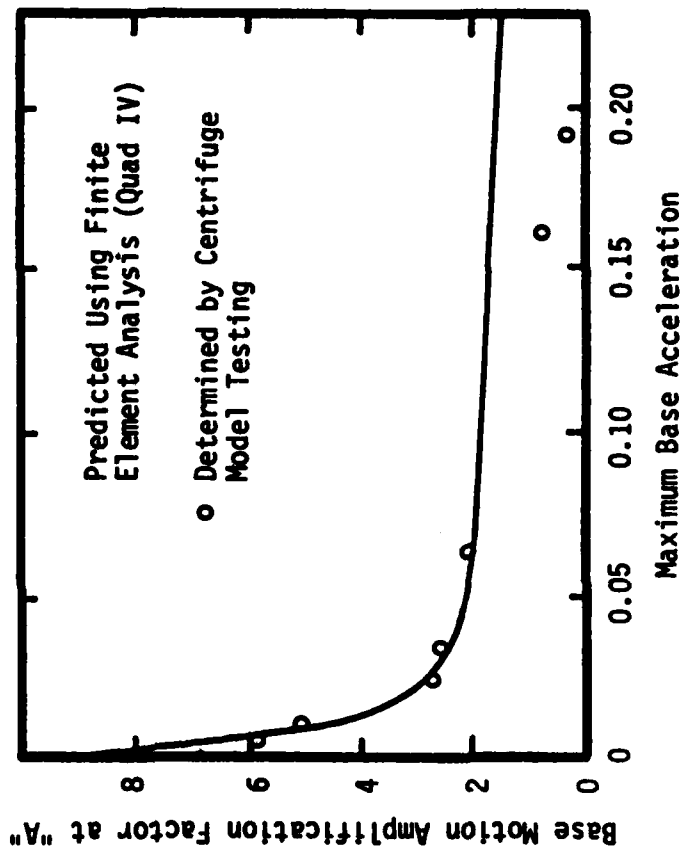
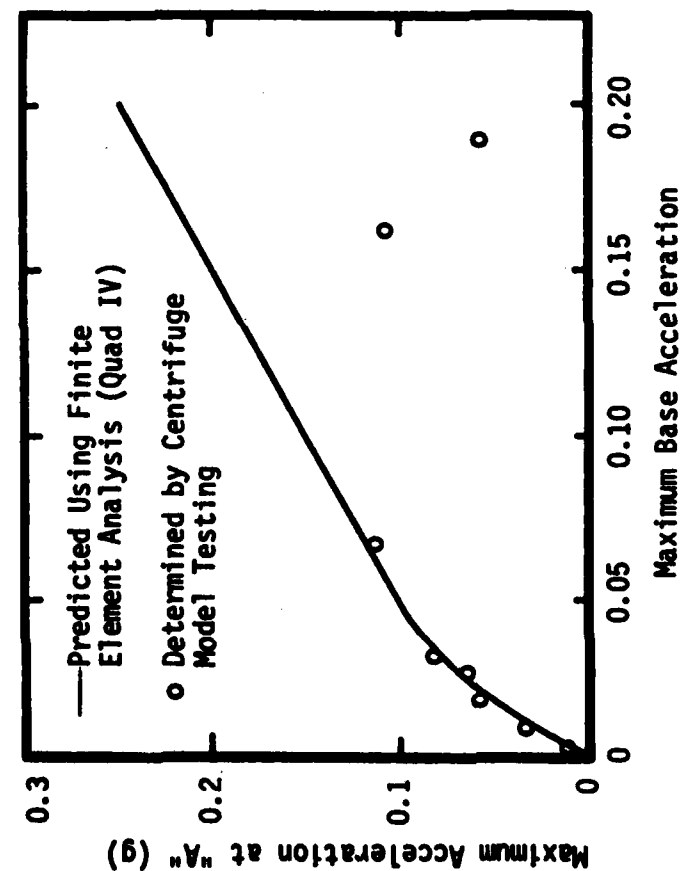


Figure 6. Comparison of Responses of Clay Embankment to Sinusoidal Base Motion Predicted by Finite Element Analysis and Centrifugal Model Testing-Model 3

## SECTION IV

### EXAMPLES OF DYNAMIC CENTRIFUGE MODELING.

Numerous examples of centrifuge modeling are available in the literature where the dynamic response and liquefaction behavior of earth structures subjected to earthquake loading were studied in the centrifuge. Anandarajah (Reference 21) has shown that dynamic response of dams predicted by centrifuge technique and by an analytical technique compared reasonably well, as shown in Figures 5 and 6. The liquefaction behavior observed in the centrifuge was shown to be very close to analytical predictions (Reference 22) as shown in Figure 7.

The offshore gravity platforms and pile-supported foundations are designed to withstand wave loading. The inertial effects in this case are negligible, whereas pore pressure build-up, soil softening, strain accumulation, etc., are important. This problem has been modeled successfully in the past (Reference 23). Footings, spread or pile, subjected to machine vibrations on the other hand require the considerations of inertial effects. In 1977, Scott (Reference 24) demonstrated the feasibility of carrying out vibration tests in the centrifuge at 100 g on a pile buried in dry sand and showed how they could be used to verify existing analytical procedures. A similar series of tests was conducted by Scott (Reference 25) to examine the dynamic load-displacement behavior of buried piles. Lateral displacement was observed to develop at an increasing rate. This was explained by the weakening of soil and degradation of the soil strength which propagates down the pile with increasing number of load cycles. Ortiz (Reference 29) investigated the dynamic behavior of cantilever retaining walls in a centrifuge.

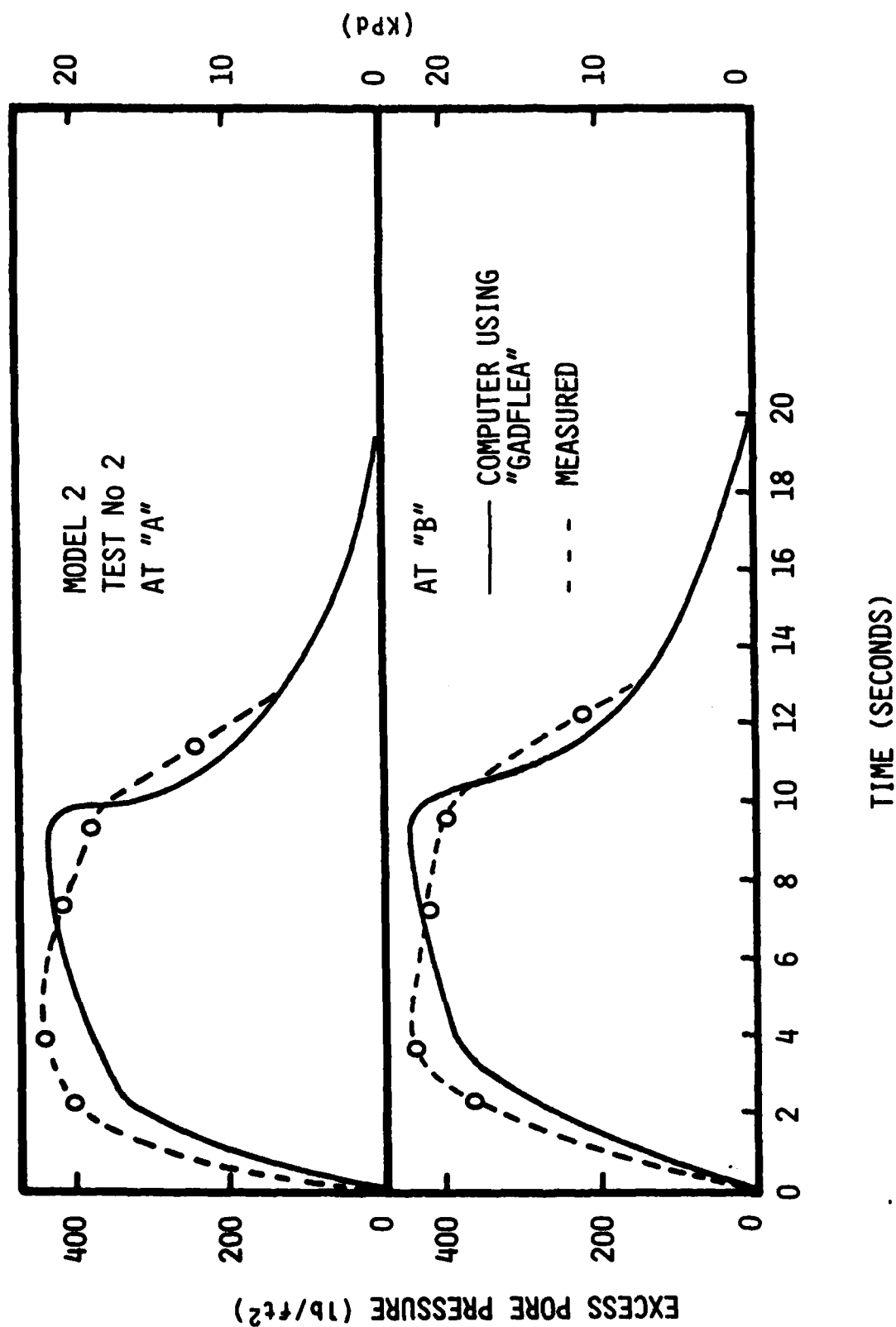


Figure 7. Comparison of Measured and Predicted Excess Pore Pressure Time



Recently, the centrifuge technique has also been used to model cratering events, blast loading, and shockwave propagation through soil media. Schmidt demonstrated the feasibility of modeling cratering event in the centrifuge in a series of papers (References 26 and 27). Nielsen (Reference 28) performed experiments in the centrifuge to model blast-loading characteristics of conventional weapons. Nielsen's research effort consisted of a series of blast events at 30 g - 80 g centrifugal accelerations. The experimental setup consisted of a burster slab resting on a soil foundation, as shown in Figure 8. Ordinary blasting cap detonators were used to simulate the weapon (Figure 9). The weight range of explosives used was from 0.2 to 0.8 grams. The centrifuge test data with the burster slab are shown in Figure 10, where the vertical normal stress,  $S(\text{psi})$  is plotted against a scaled distance,  $\lambda = R/W^{1/3}$  ( $\text{Ft/lb}^{1/3}$ ). Here  $R$  is the distance in feet from the explosive and  $W$  is the weight of the explosive in pounds. The best fit to the data shown in Figure 10 is:

$$S = 5879 \lambda^{-1.325}$$

This research effort demonstrated the feasibility of using a centrifuge to physically model the conventional weapons effects.

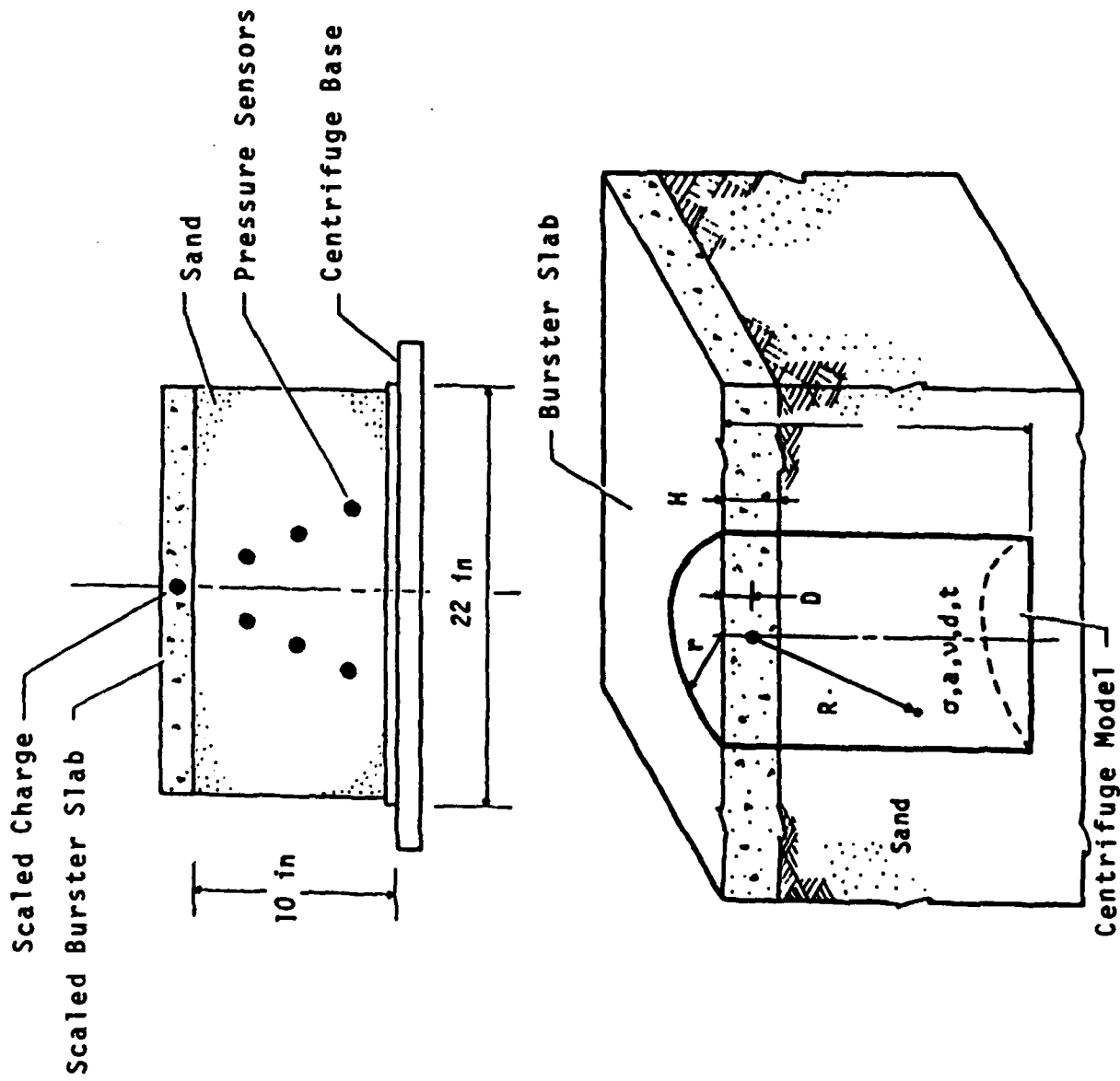


Figure 8. Prototype System and Centrifuge Model

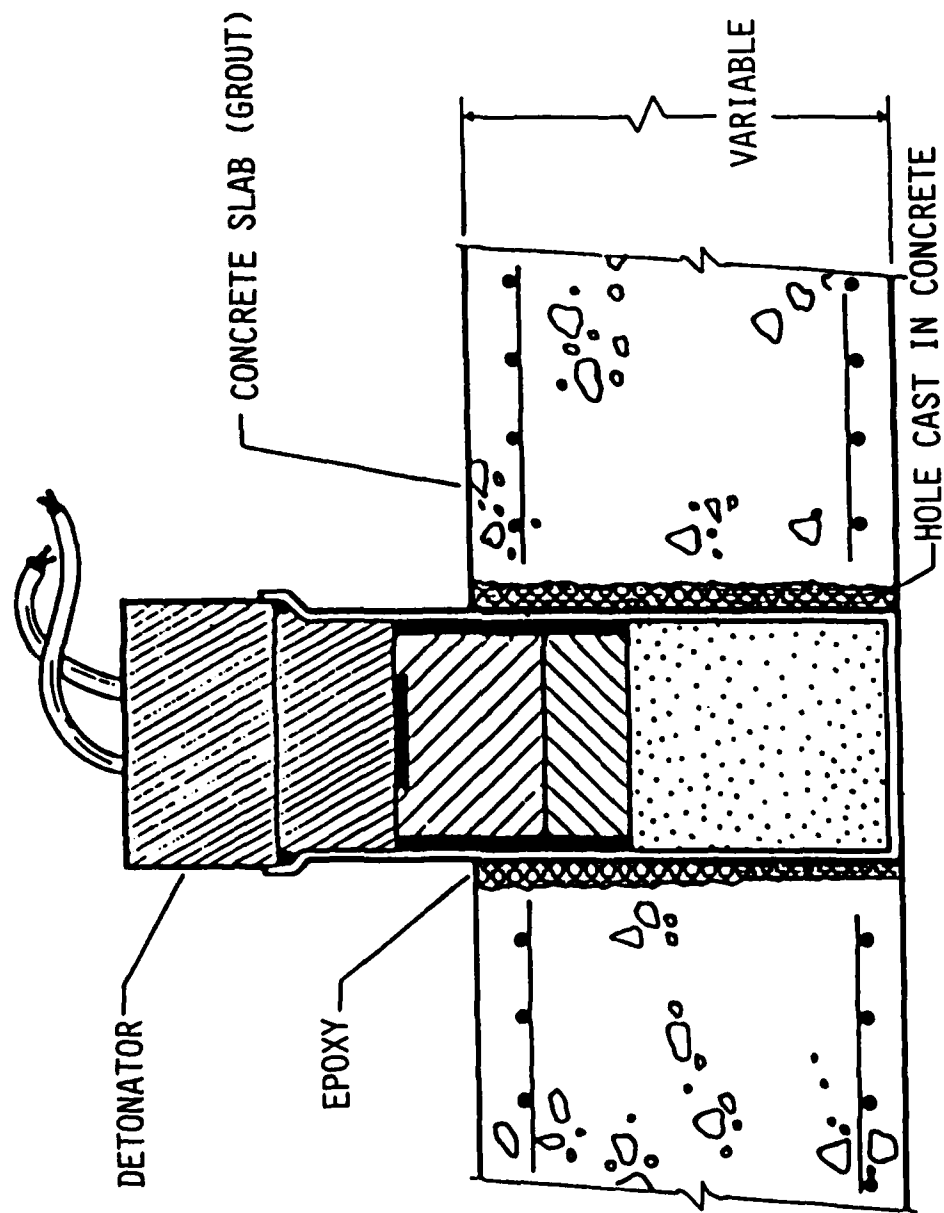


Figure 9. Placement of Detonator in Burster Slab

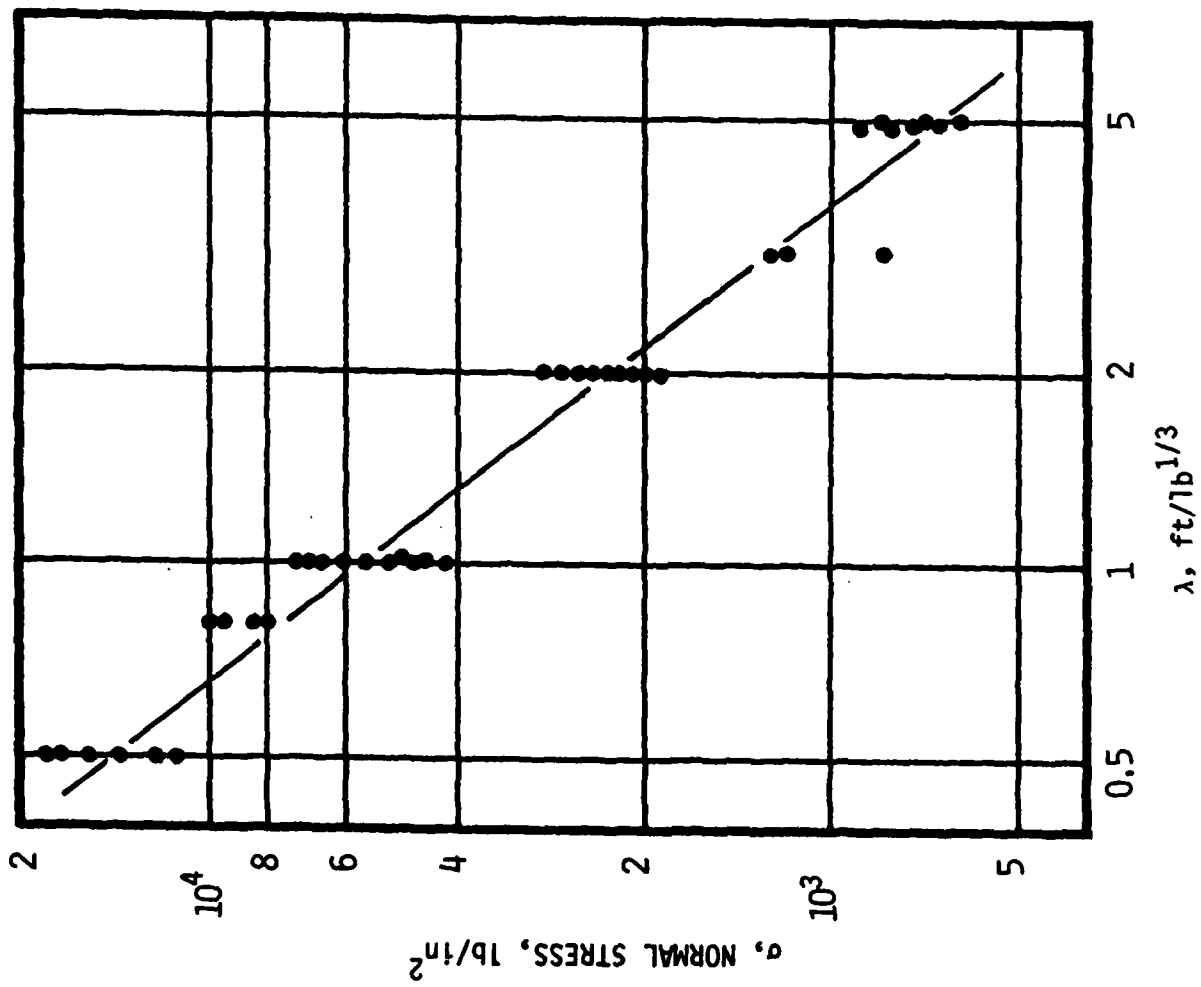


Figure 10. Data for Tests with a Burster Slab

## SECTION V

### ADVANTAGES OF USING CENTRIFUGE MODELING TECHNIQUE TO STUDY THE BEHAVIOR OF GEOTECHNICAL STRUCTURES

Several advantages of centrifuge modeling are listed below.

1. Prototype stresses and strains are correctly modeled.
2. It provides a means of verifying theories which in some cases, particularly under earthquake-loading conditions, is very difficult if not impossible.
3. It provides a relatively inexpensive means of directly assessing (a) the influence of soil type, water content, structural material type, etc. on the structural behavior, and (b) effectiveness of the methods of protecting underground and surface structure against shock and earthquake loading.
4. It provides a means of directly observing the deformation processes and failure mechanisms with the aid of video cameras, high-speed cameras and suitable transducers.

There are numerous other advantages of using a centrifuge for geotechnical modeling, depending on the loading and test conditions. The full potential of the techniques, however, can only be realized in a large-capacity centrifuge such as the National Geotechnical Centrifuge Facility at Ames, California, USA (Figure 1). This allows a large-size model (6 feet by 6 feet by 5 feet) to be tested which, in turn, permits extensive instrumentation and modeling details. The boundary effects are also reduced by testing models in large buckets. This further permits modeling of models at a broader range of scales.

## SECTION VI

### SUMMARY AND CONCLUSIONS

→ The centrifuge modeling technique has a tremendous potential for experimentally determining the behavior of soils and soil-structure interaction problems. The prototype stresses and strains are correctly modeled in a centrifuge model by the application of centrifugal acceleration. Past experiments clearly demonstrate the feasibility of performing dynamic centrifuge modeling under earthquake-loading, machine vibration, and blast-loading environments. There are, however, difficulties associated with dynamic centrifuge modeling; some of which can be overcome by performing experiments in large capacity centrifuges. The remaining difficulties require further research and development.

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